Chalmers Industrial Case Study Portfolio – Contents, Structure and Example Applications

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1 Introduction

To reach international and national targets for climate gas reductions over the coming decades, a transformation is needed in all sectors including the manufacturing industry. A wide range of measures are needed to achieve the greenhouse gas emissions reduction targets. Opportunities for radical reduction of emissions from industrial sites include process electrification, carbon capture, renewable feedstock and energy supply and a better utilization of excess heat.

There is a pressing need to better understand the effects and consequences associated with different options for the industrial energy transformation in order to evaluate the potential to reach required climate goals. Techno-economic analysis (TEA) and environmental life cycle analysis (LCA) are examples of methods that can be used to model and understand the economic and environmental impacts of such changes. If the required rapid transformation of the energy system will actually be implemented in all sectors, new industrial technology and processes will operate in a system that differs significantly from the current one with respect to, for example, energy demands, infrastructure and energy market conditions. The methods for evaluating the techno-economic and environmental impacts of the industrial transitions need to account for this development, both within and outside of the industrial sector.

This need can be illustrated by evaluation of the potential to recover excess heat from industry and use it to supply heat to a district heating network. Such an assessment needs to account for the changing heating demand in the buildings sector as well as the fact that excess heat availability from industrial processes is likely to change considerably following the foreseen improvements in internal heat recovery, industrial electrification and changes in heat demand due to the integration of new biobased processes or carbon capture. While the industrial heating and cooling demand has changed gradually over time, the need for drastic emission cuts in the short-term implies that these changes are expected to happen much faster and much more radically.

Consequently, to enable modelling, assessment and comparison of different technology pathways for the industrial energy transition, there is a need for data that describes not only current energy and emission balances of industrial sectors, but also how these might change over time. In order to achieve this, detailed data for the heating and cooling demands of the industrial processes are needed, which can then be used to estimate how the energy and emission balances would change if unit processes are replaced by new technology or new processes are integrated with or replacing the existing ones. At this level of detail, it is essential to be aware of the significant heterogeneity of the industrial sector. For the largest emitting sectors (in Sweden: pulp and paper, iron and steel, cement, oil refining and chemicals), the differences are considerable between different subsectors and even between individual sites within the same subsector. This creates a need for detailed case studies as a basis for bottom-up evaluations, as evidenced by the literature review presented in Section 2.

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At Chalmers University of Technology, an extensive number of case studies of industrial sites have been carried out and used as a basis for research projects investigating the consequences of enhanced heat recovery, implementation of new process technology, industrial symbiosis in industrial clusters, etc. Data from these studies is a valuable resource for future studies related to radical emission cuts in industry that require site-specific information about the industrial plants' energy systems. By collecting and compiling these case studies in a portfolio, we believe that data and knowledge from previous studies can be better utilized, both for individual case study examples illustrating future directions and consequences of the integration of new technology, as well as for studies aiming at assessing the aggregated potentials and effects of industrial energy use.

After a non-comprehensive review of related work in Section 2, this report describes the structure and content of *Chalmers Industrial Case Study Portfolio* (ChICaSP) (Section 3) and demonstrates how the case study portfolio was used to support the evaluation of available industrial excess heat for carbon capture in Sweden (Section 4 and 5). Section 4 describes how data available from a single case study was used for further assessment of excess heat availability from one specific site, and thereby illustrates the value of having access to this kind of detailed data for internal heating and cooling demands for assessing future changes in a plant's energy system. Section 5 describes how easily accessible data for all relevant sites in Sweden enabled a more aggregated assessment of the potential to use industrial excess heat for carbon capture on the national level.

2 Related work – Data and models of industrial energy use

Bottom-up approaches for modelling industrial energy use is a necessity for being able to capture the major heterogeneity of the industrial sector with sufficient detail with respect to, for example, geographic explicitness or temperature-heat load characteristics. However, bottom-up approaches lead to difficulties related to data availability due to the complexity of the industrial sector with its large diversity of industrial production processes. For example, Rehfeldt et al. (2018) argue in their introduction that there is a need for more detailed (less aggregated) data for industrial energy end-use. According to them, the lack of detailed, comparable and reliable data on energy end-use for the industrial sector can be explained by general difficulties of colleting detailed energy demand data as well as by industry-specific challenges. To evaluate process heating demands, detailed knowledge about the characteristics of industrial process unit operations is required. Other authors confirm that data availability is a constraining factor in studies of industrial energy systems. To cite two such studies, Brueckner et al. (2014) conclude in their review of methods for estimation of industrial waste heat potentials that "lack of data is a very huge obstacle to the quantification and usage of the industrial waste heat" and Naegler et al. (2015) conclude that "A serious obstacle in this study is the difficulty to obtain reliable, up-to-date data on energy usage and PH [process heating] temperature levels on a national and industry branch level."

The difficulties associated with data availability lead to industrial energy use often being handled by modelling the energy demand on the subsector level, with subsector referring to e.g. the chemical industry, cement industry or pulp and paper industry. However, efforts have been made to capture also the energy end-use category (e.g. process heating, space heating, lighting, mechanical energy etc) and the temperature levels of process heating and cooling in the bottom-up models. For example, both Pardo et al. (2013) and Naegler et al. (2015) assign a share of final energy to process heating and cooling and pre-defined temperature levels. However, they assume that the share of process heating in final energy use is fixed in each subsector (i.e. a single fixed share value is used for the whole pulp and paper industry). Consequently, they fail to capture the heterogeneity within subsectors, such as substantial differences in technology and processes between, e.g., chemical and mechanical pulping and between market pulp mills and integrated pulp and paper mills.

In the work of Rehfeldt et al. (2018), an important step is taken towards improved industrial energy end-use balances. In their work, a methodology is proposed to differentiate industrial energy end-use, not only by subsector and energy carrier, but also by user category (process heating/cooling, space heating, and other), and to divide the process heating demands by temperature level. The results from their bottom-up modelling is combined with top-down statistics for the national subsector energy use and are shown to match these quite well. However, their model is based on assumptions such as "process equals process", meaning that a certain process is assumed to have the same specific energy consumption independently of its location. Through this assumption, differences in the level of heat recovery are neglected, both within a given process and between different processes at the same industrial site. The approach also fails to consider integration between industry and other sectors, such as the integration with district heating systems and combined heat and power plants. It is also worth noting that the specific energy consumption is highly dependent on the considered boundary of a process. The process boundary definitions used vary substantially, where a "process" sometimes refers to a single process step, sometimes to the entire process chain from raw material to final product. This lack of consistency, although unavoidable due to the constraints set by data availability, makes it even more difficult to consider current and future potential for heat recovery and process integration. Furthermore, the share of different energy carriers is taken as averages per subsector and, consequently, cannot be investigated at the process level. Generally, while the proposed methodology seems suitable for its purpose of describing industrial energy-end use balances divided per user category, temperature level and country, other approaches are needed when the purpose requires site-specific information related to available infrastructure, process integration and current technology and emission levels.

On the other hand, there are many studies and data sources that describe energy use in specific industrial processes, especially the more important ones in terms of energy intensity. One of the more complete reference works is the characterization of 108 industrial processes by Brown et al. (1996). However, this type of process description provides detailed technical specifications including temperature levels of heat demands but does not present or relate this to the total energy use on a sector or regional level. And while this type of descriptions applies to generic process designs (typically either average or BAT), no information is provided about which technology is used at a given site, nor to what extent various energy efficiency measures are already implemented. Furthermore, the descriptions need to be continuously updated as technology and processes develop over time, continuously requiring significant efforts in data collection.

Similar technology and process databases have been used as a basis in modelling frameworks for energy analysis of industrial sectors and regions. A recent contribution, which illustrates the great opportunities offered by comprehensive databases and modelling frameworks, is given by Talaei et al. (2018) who study the mid- to long-term energy efficiency and GHG mitigation potential of the chemical industry in Alberta, Canada. The work uses the Long-range Energy Alternatives Planning (LEAP) model, which has a built-in Technological and Environmental Database (TED) where the detailed environmental impacts of different processes and fuel combustion are available (Heaps, 2016). Published studies of this type (bottom-up modelling frameworks based on subsector plant and technology databases) are, however, very data-intensive and therefore typically limited to one sector and one region. For example, in the study of Alberta's chemical industry, the scope is not only limited to Alberta and the chemical sector, but to include detailed investigations of only the most energy-intensive processes. Another example is RISI's asset database for pulp and paper mills (RISI, 2018), in which data is available describing current mill equipment, age structure and investment history. One of the uses of this database is as input to a bottom-up modelling framework for the analysis of the energy transition in the European pulp and paper industry up to 2050 (Moya and Pavel, 2018), which considers the technological details of each facility to simulate a cost-effective uptake of energy efficiency measures and breakthrough technology innovations. As far as we can tell, however, the modelling framework does not seem to include any information about the current degree of heat recovery in the mills, and the potential savings from process heat integration as an energy efficiency measure is set as a generic value per ton of product. While the proposed approaches should be applicable to other regions or subsectors, the practical opportunity for extending their scope relies heavily on the availability of key data for a region's industrial sites as well as for the main industrial processes of the studied sector.

For studies addressing some more specific applications or technologies related to industrial process heat, the use of databases with site-specific information is more wide-spread. Examples include studies that map the availability of industrial residual heat, such as Persson et al.'s (2014) Heat Roadmap Europe, which is based on a top-down approach and McKenna and Norman's (2010) spatially explicit modelling of industrial heat recovery potentials in the UK, whose bottom-up approach was also recently adopted by Miró et al. (2018). In the application of residual heat recovery, the spatial explicitness is of high importance, since the usefulness of excess heat from the industrial site depends on the geographic closeness to other industrial sites and existing or potential new district heating systems. Another example are studies of industrial carbon capture for which the feasibility relies on availability of infrastructure for transport and storage. For example, Rootzén et al (2011) extended the Chalmers Energy Infrastructure Database (Kjärstad and Johnsson, 2007) with a database of industrial facilities to study the role of carbon capture and storage in European industry and considered sector- as well as site-specific conditions for capture. However, even if these studies use site-specific information for CO_2 emissions and/or production rates, process heat flows (if considered at all) are estimated using fixed, non-site-specific factors to relate production and emission values to primary energy consumption and heat recovery levels. While these studies are based on site-specific data that are of high importance for the topic investigated (such as the geographic closeness to district heating systems or CO_2 storage sites), they do not usually provide a complete picture of a site's process heating and cooling demands that can be used to study other technology pathways or the system effects of integrating several new processes or solutions at the same site. For example, the studies of waste heat potentials typically consider the availability of heat from current processes, and not how these would change by the integration of excess heat-driven post-combustion carbon capture, new biobased processes, or extensive process electrification.

To summarize, very few, if any, databases and general modelling frameworks provide comprehensive data on process heating and cooling demand at a level of detail that makes it possible to evaluate systems solutions and process integration effects of implementing different technologies, and that also take into account site-specific conditions. Examples of questions that could be answered with this type of information are: How are industrial heat recovery systems affected by wide-spread adoption of decarbonisation technologies such as electrification, carbon capture or biorefining? What are the consequences for heat integration within the process and between processes? How is the availability of excess heat affected? How will the potential for co-generation change? And in the end, which combination of measures is likely to result in the greatest benefits in terms of climate mitigation?

The literature cited above, although not presenting a complete literature review, makes it clear that availability of data is a key challenge for industrial energy systems studies. Consequently, the value of individual case studies as a ground for databases, modelling assumptions and analysis should be very high, especially if the case studies are connected to national statistics and publicly available data of site-specific emissions, geographic locations, production rates etc.

3 Chalmers Industrial Case Study Portfolio – Structure and content

Chalmers Industrial Case Study Portfolio (ChICaSP) consists of a number of files containing data for the major industrial sites in Sweden, references to relevant literature, and a library of publications.

3.1 Structure of the portfolio

The structure of the portfolio is illustrated in Figure 1, which also provides an indication of the type of information and material available in the portfolio.

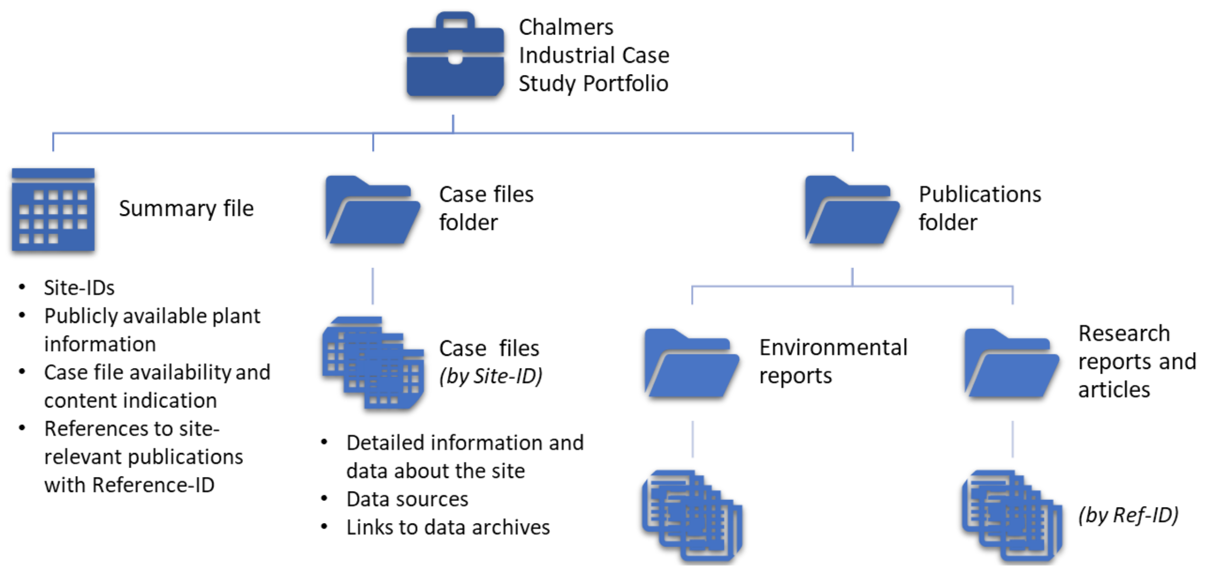

Figure 1. Structure and indicative contents of Chalmers Industrial Case Study Portfolio.

An important feature of the portfolio is the separation of content based on the levels of details and public availability of the information. The main file of the portfolio is the summary file (see Section 3.1.1) containing publicly available data for all industrial sites fulfilling the criteria for inclusion and gives an overview of the portfolio content. More detailed information about the individual sites is reported in separate case files (see Section 3.1.2). The portfolio also contains publications relevant for included sites. The case files and publications are easily located through the summary file and a systematic use of Site and Reference IDs.

In September 2018, the summary file of ChICaSP contained a list of 70 large industrial sites in Sweden within the mineral extraction and manufacturing sectors (Swedish SNI-codes 05-33, SNI05-33). For 38 sites, case files containing a more detailed overview of the energy situation existed.

The sites in ChICaSP were selected based primarily on total CO_2 emissions (65 sites of the total 70 included sites), and all sites reporting CO_2 emissions (fossil + biogenic) totalling more than 50 000 ton/year for 2016 were included. All but one of the included sites were part of the European Union's emission trading system (EU-ETS). The remaining five sites were included because their latest reported (net) annual electricity consumption exceeded 200 GWh. This extension was made because of an ambition to include all sites with significant energy use, regardless of on-site CO_2 emissions. Since no exhaustive list of Sweden's largest electricity consumers was available when the portfolio was compiled, it cannot be guaranteed that all sites consuming more than 200 GWh/year of electricity were included when the portfolio was originally compiled.

3.1.1 Summary file

The summary file contains an indexed list of all 70 sites fulfilling the criteria of CO_2 emissions and/or electricity consumption. The summary file contains general, publicly available, information about the sites, full bibliographic information for all sources and site-relevant publications, and information about the sites' case files. The latter includes information regarding whether a case file is available or not, and what type of data it contains. Table 1 lists the publicly available data gathered in the summary file. This information is based on data which is reported annually to government agencies, industry organisations and similar. A selection of content from the Summary file is shown in Appendix A.

Table 1. Publicly available data in the ChICaSP Summary file.

Data entry	Unit	Source
Site coordinates according to WGS84	Decimal degrees (DD)	European Pollutant Release and Transfer Register (PRTR) (EEA, 2016)
County and Municipality		Swedish PRTR (SEPA, 2016b)
Industrial sector		Swedish Environmental Protection Agency. Classification. Same classification used for reporting of greenhouse gas emissions to Statistics Sweden (SCB, 2016) and for managing statistics related to the EU-ETS (SEPA, 2016a).
Type of site/mill/plant		Various sources, incl. company environmental report, web pages, etc.
Emitted CO2: fossil, biogenic, total	ton/year	Fossil emissions: Data reported within the EU-ETS, in Sweden compiled by the Swedish Environmental Protection Agency (SEPA, 2016a). Biogenic emissions and fossil emissions for sites not covered by the EU-ETS: Swedish PRTR, based on data reported to the Swedish Environmental Protection Agency (SEPA, 2016b)
Net electricity consumption	GWh/year	Company environmental reports. For pulp and paper mills, data from environmental reports are available in the forestry industries' environmental database, which has been used as the primary source (Skogsindustrierna, 2016). A few additional sources, such as company web sites, have been used when the environmental reports have not been available or are lacking information.
Gross heat exports	GWh/year	
Annual production	tons	

3.1.2 Case files

The case files are generally based on data gathered within research projects (including MSc. Theses) conducted at Chalmers, but similar data from other actors have been used in some cases. While the data underlying the summary file is updated annually, the case files are based on data gathered at a specific occasion for a specific use. Compared to the summary file, a case file contains more detailed information about a site's energy situation. Appendix B contains some examples of contents from one of the case files in the portfolio.

All case files include some general information, for example a date for creation of the case file, and information regarding data sources used. The latter includes references to published data and directions to project data archives. Additionally, an indication is given about whether some of the data is subject to confidentiality constraints. In the case files, data will typically also be available in some or several of the areas described in Table 2.

Several data sources are often required to be able to enter as much information as possible in the case file. The case file allows for specifying which data sources has been used for each type of data. For most sites, the case files contain a combination of data that is available in published reports or articles, and unpublished data from project archives. Pinch analysis data is a typical example, where curves representing a site's net heating and cooling demands may have been published while the underlying stream data is only available in the project archive.

Table 2. Main sections of the case file template

Data section	Description
General information	Sources, confidentiality and other types of general case file information
Overall balance	Overall mass and energy balances of the plant, including resource consumption, emissions, energy use, production levels and similar
Process description	Overview of the production processes at the site. Generally presented as a process flow sheet
CO_2 sources	Typically presents flue gas specifications for different stacks
Utility system	Description and data for the internal site energy system, which generally refers to the steam system with boilers, turbines etc
Pinch analysis	Pinch analysis including stream data, resulting pinch curves and the assumptions and system boundaries used for the analysis
Existing heat exchanger network	Information about the existing heat exchanger network structure, or the placement of existing heaters and coolers
Excess heat	Available assessments of excess heat

3.1.3 Publications

All sites included in ChICaSP are obliged to submit an annual environmental report, either to the relevant county administrative board (Länsstyrelse in Swedish) or the corresponding authority on the municipality level. Environmental reports that have been collected by requesting them from the authorities or by downloading them from web pages are gathered in a ChICaSP folder. The reports have mainly been used to establish the annual production levels and electricity consumption of the included sites. However, plenty of other environmental and energy related data is available in these reports.

All publications used as data sources for the case files are also directly available in the portfolio. In addition, some publications which have not been used as data source, but still contain information related to a ChICaSP site, have been included. All publications are tagged with the publication-ID given in the ChICaSP summary file.

3.2 Coverage of the portfolio

In 2016, the fossil CO_2 emitted by the 70 sites included in the summary file of the industrial case study portfolio corresponded to 86 % of the total fossil CO_2 emissions for Swedish industry, and more than 90 % of the Swedish industry's emissions within the EU-ETS. The coverage per industrial sector (included fossil emissions related to total fossil emissions for that sector) is listed in Table 3. The total fossil emissions per industrial sector are based on figures reported by the Swedish Environmental Protection Agency to Statistics Sweden (SCB, 2016).

The database also includes large point sources of biogenic emissions. The biogenic emissions are not reported consistently in different databases, which makes it more difficult to determine the coverage of biogenic emissions in the portfolio. For example, Statistics Sweden report total industrial biogenic CO_2 emissions of 6 937 ktonnes (SCB, 2016), which is significantly less than the biogenic CO_2 emissions reported to the Swedish Pollutant Release and Transfer Register (PRTR). Only by including sites producing pulp and paper, the total biogenic emissions sum up to 22 140 ktonnes. In principle, all but a few sites which report biogenic CO_2 emissions to the PRTR are included in ChICaSP, as indicated in Table 4.

Table 3: Number of sites and total fossil CO_2 emissions included in the industrial case study portfolio per industrial sector. In the fourth column, the fossil emissions for sites included in ChICaSP are related to the total fossil emissions for that industry as reported by Statistics Sweden (including emissions not covered by EU-ETS).

Industrial sector[a]	Number of sites	Included fossil emissions 2016 (1000 ton)	Share of sector's fossil emissions
Iron- and steel industry	10	5612	93 %
Chemical industry	6	1057	75 %
Food industry	2	86	21 %
Metals industry (excl. Iron and steel)	3	591	87 %
Minerals industry (excl. metals)	9	2995	94 %
Pulp-, paper- and printing industry	32	611	84 %
Refineries (incl. Distribution of oil and gas)	4	2608	98 %
Other industry (mines, wood manufacturing industry, etc.)	4	750	56 %

[a] The sector classification of the sites agrees with the one used by the Swedish Environmental Protection Agency for the reporting of greenhouse gas emissions to Statistics Sweden (SCB, 2016) and for managing statistics related to the EU-ETS (SEPA, 2016a).

Table 4. Total biogenic CO_2 emissions included in the industrial case study portfolio per industrial sector. In the third column, the biogenic emissions for sites included in ChICaSP are related to the total biogenic emissions for the corresponding PRTR activities as reported to the Swedish PRTR.

Industrial sector[a]	Included biogenic emissions 2016 (1000 ton)	Share of biogenic emissions reported to the Swedish PRTR	PRTR activities
Iron- and steel industry	0	[b]	2.(a)-(d)
Chemical industry	0	[b]	4.
Food industry	75	97%	8.
Metals industry (excl. Iron and steel)	1	100%	2.(e)-(f)
Minerals industry (excl. metals)	180	100%	3.
Pulp-, paper- and printing industry	22 082	~100%	6.(a)-(b)
Refineries (incl. Distribution of oil and gas)	0	[b]	1.(a)
Other industry (mines, wood manufacturing industry, etc.)	0	[b]	e.g. 6.(c), 9.

[a] Biogenic emissions are not reported according to the same industrial classification as is used by Statistics Sweden, EU-ETS and ChICaSP. Instead, biogenic emissions are reported to the Swedish Pollutant Release and Transfer Register (PRTR) according to site activity classifications. The PRTR activities that have been used to estimate total biogenic emissions for each sector are given in the rightmost column.

[b] No biogenic CO_2 emissions reported for these PRTR activities

Table 5 presents the total electricity consumption, per industrial sector, of the sites included in the ChICaSP summary file, and for which this number was available (60 out of 70 sites). The number is compared to the total consumption for each sector. Total electricity consumption per industrial sector is based on data reported by the Swedish Energy Agency for 2016 (SEA, 2016).

Table 5: Total electricity consumption for included sites, per sector. Note that electricity consumption is not available for all included sites. The third column lists the share of total electricity consumption deriving from the included sites, and the fourth column lists the SNI codes used to estimate total consumption.

Industrial sector[a]	Included electricity consumption 2015/2016/2017 [b] (GWh/år)	Share of sector's consumption (2016)	SNI2007
Iron- and steel industry	3175	72 %	24.1–24.3
Chemical industry	1443	31 %	20-21
Food industry	175	7 %	10-12
Metals industry (excl. Iron and steel)	2808	92 %	24.4–24.5
Minerals industry (excl. metals)	59**	6 %[c]	23
Pulp-, paper- and printing industry	17763	88 %	17
Refineries (incl. Distribution of oil and gas)	827	85 %	19
Other industry (mines, wood manufacturing industry, etc.)	3020	84 %	05-09

[a] Data statistics on electricity consumption does not follow the same industrial classification as is used for reporting to EU-ETS (and thereby in ChICaSP). Instead, electricity consumption is reported following the SNI2007 classification. The SNI-codes that have been used to estimate total electricity consumption for each sector are given in the rightmost column.

[b] Data is from 2016 if available. If not, data is from latest available environmental report (mostly 2017, occasionally 2015).

[c] Figure is unavailable for 7 out of 9 sites.

4 Opportunities offered by access to case file data – Example of excess heat assessment for a pulp mill

This section describes how detailed data available from a single case study can be used for further assessments that were not previously studied, but which are of interest as part of a new study. In this example, data from a ChICaSP case file was used to estimate the availability of excess heat for carbon capture.

Previous work by Gardarsdottìr et al. (2018) identified steam costs as the single parameter with the highest influence on total capture costs for industrial carbon capture, thus underlining the importance of a cheap heat supply, such as excess heat. In a later project, a novel solvent was studied, which could allow for lower temperature requirements for solvent regeneration, and consequently enable the use of lower temperature excess heat sources. For the estimation of industrial excess heat availability, two main temperature scenarios were considered, corresponding to the lower and higher range for the temperature requirement assumed for the novel solvent: Excess heat of 95 °C and 110 °C, respectively. In general, the results were also compared to the requirements set for using a benchmark amine solvent (Excess heat temperature requirement approximately 140 °C).

4.1 The case study mill

The industrial site chosen for this demonstrating example is the SCA Östrand pulp mill, which is a non-integrated Kraft pulp mill.

The production capacity of the SCA Östrand mill was recently increased significantly through a major reconstruction project. The new mill was started up in June 2018 (SCA, 2018). In 2015, a pinch study was conducted to identify possible improvements in the design of the heat recovery system of what was then a prospected mill (Ahlström och Benzon, 2015). At the time of the pinch study, data for full production was not available. Instead, predicted values for the prospective reconstructed mill were based partly on quotations and partly on up-scaled data from current operation. This is the data that has been entered in the case file for SCA Östrand in ChICaSP. Selected content from the ChICaSP case file for the mill is presented in Appendix B.

The pinch analysis is representative for a mill production of 900 000 tonnes of Kraft pulp per year. The investigated production scenario of 900 000 tonnes/year of Kraft pulp corresponds to a scale-up factor of 2.1 from the production capacity before the reconstruction (430 000 tonne/year).

4.2 The mill utility system

In addition to the recovery boiler, the mill is equipped with a bio-boiler. This boiler will be used for firing of bark and wood powder. According to the environmental permit application for the production increase (MMD, 2016) the steam capacity of the recovery boiler after the reconstruction will be approximately 550 MW, and the steam capacity of the bio-boiler approximately 127 MW when fuelled with bark and wood powder. Operating the boilers at these loads would, however, lead to a large steam excess. The mill therefore also invests in a condensing turbine for additional power generation on site. Steam is extracted from the turbines at several different pressure levels, but the main steam flows go to the medium pressure (MP) and low pressure (LP) steam headers at 12 and 4.7 bar, respectively (see Figure 2). It is assumed here that the recovery boiler is operated at maximum capacity during normal operation.

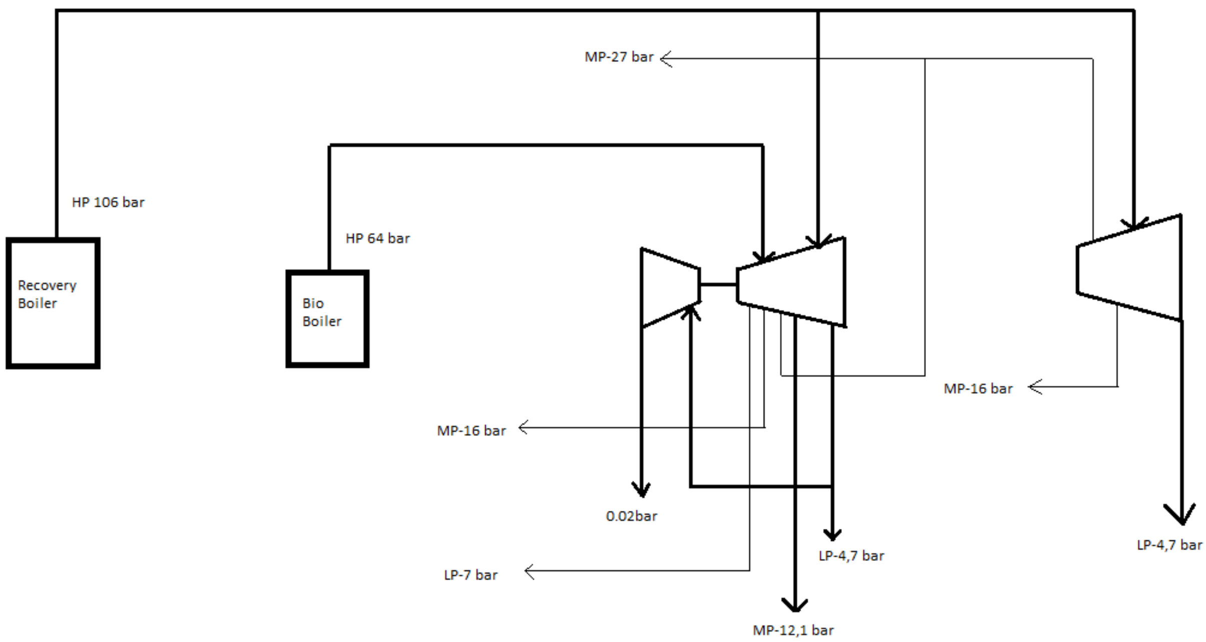

Figure 2. Prospected steam utility system of the SCA Östrand mill. Source: (Ahlström och Benzon, 2015).

4.3 Excess heat availability

The availability of excess heat has been analysed for two distinct assumptions: an ideally heat integrated process and the actual design of the process. The first case is described in Section 4.3.1 and represents a theoretical situation assuming extensive internal process heat recovery. The second case, in which excess heat is represented by the current cooling demand of the process, is described in Section 0.

4.3.1 Theoretical excess heat availability after maximized internal heat recovery

First, the excess heat availability after ideal internal process heat integration and maximized electricity generation is evaluated. This excess heat can be referred to as “true” or “unavoidable” excess heat. The assessment follows an approach used in previous work (see Svensson et al., 2018), which is summarized in Appendix C.

To complete the assessment, stream data from the case file has been adapted and analysed further. In particular, streams representing heating and cooling demands related to the utility system, such as feed water preheating and cooling of flue gases from the bark boiler, have been removed before continuing the targeting assessments. These heating and cooling demands are instead considered in the integration of the boilers and steam cycle and depend therefore on the sizing of these systems.

For heat exchange within the process, or between the process and boiler flue gases, or steam system, it was decided to keep the assumed minimum temperature approach contributions for the process streams, as specified in the stream data. For heat delivered to a potential carbon capture process, the requirement is set as a minimum real temperature of the process streams providing the heat at either 95°C or 110°C.

Figure 3 shows the net heating and cooling demand of the process including the heat available from the recovery boiler (orange) together with a simplified integrated steam cycle with a condensing stage (blue dashed). Note that the heat demand for raising steam is exactly covered through this integration. The heat from the bark boiler is not included in these curves. Consequently, it can be seen that, at least theoretically, the recovery boiler is sufficient for covering the steam demand of the process and can even generate a surplus of steam for condensing power production.

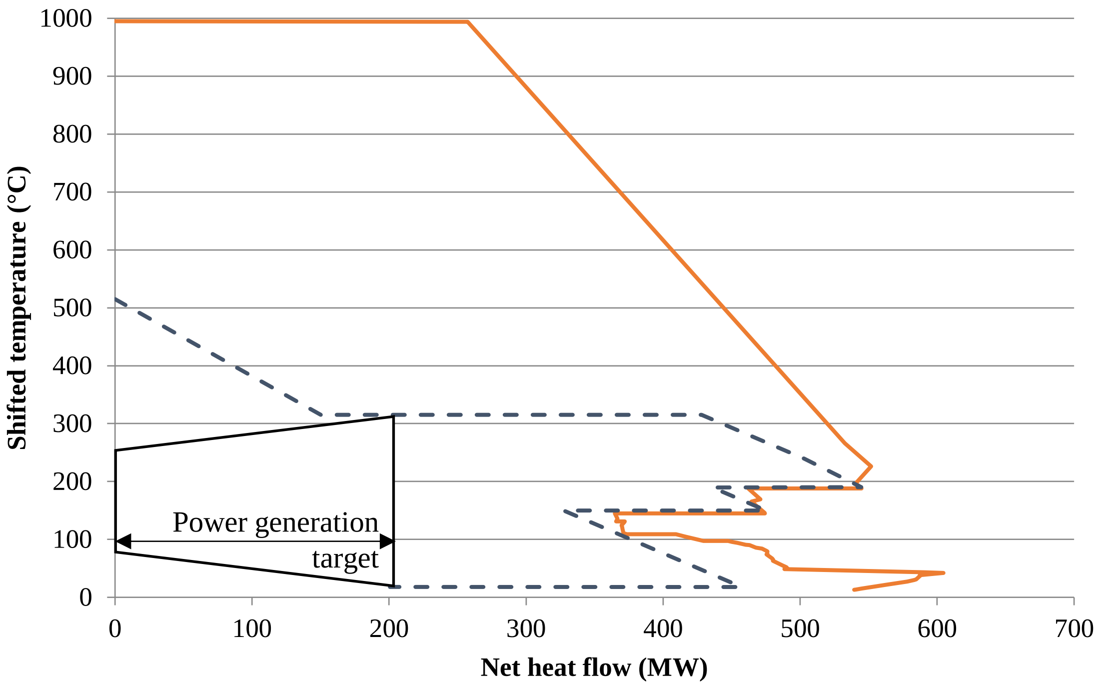

Figure 3. Integration of steam cycle (blue, dashed line) with the pulp mill process (orange, solid line). The grand composite curve for the pulp mill includes the heat from combustion in the recovery boiler, but ***not*** *the bark boiler. The steam cycle includes a condensing stage. ΔT_{min} is set individually for each process stream according to stream data as presented in Appendix B.*

The curves in Figure 3 could be constructed from the data available in the case file for the mill, which contains data about the heating and cooling demand of the pulping process, and steam header specifications that determine the temperatures of the steam turbine extractions (as specified in Figure 3). For the analysis presented here, this is complemented only by the estimated heat available from the recovery boiler. Figure 3 also illustrates how heat from the process can be used to cover the heating demand of the return condensate from the condensing turbine.

Despite the heat demand for re-heating the turbine condensate, it is possible to extract another 65 MW of heat from the process at temperatures of 97°C and higher (e.g. as indicated in Figure 4). This can be accomplished by heating the turbine condensate partly with lower temperature heat from the process. The 65 MW can thus be extracted even after the process is ideally integrated, with maximized electricity generation, and without utilizing the bark boiler, and can thereby be considered to be ”true” excess heat.

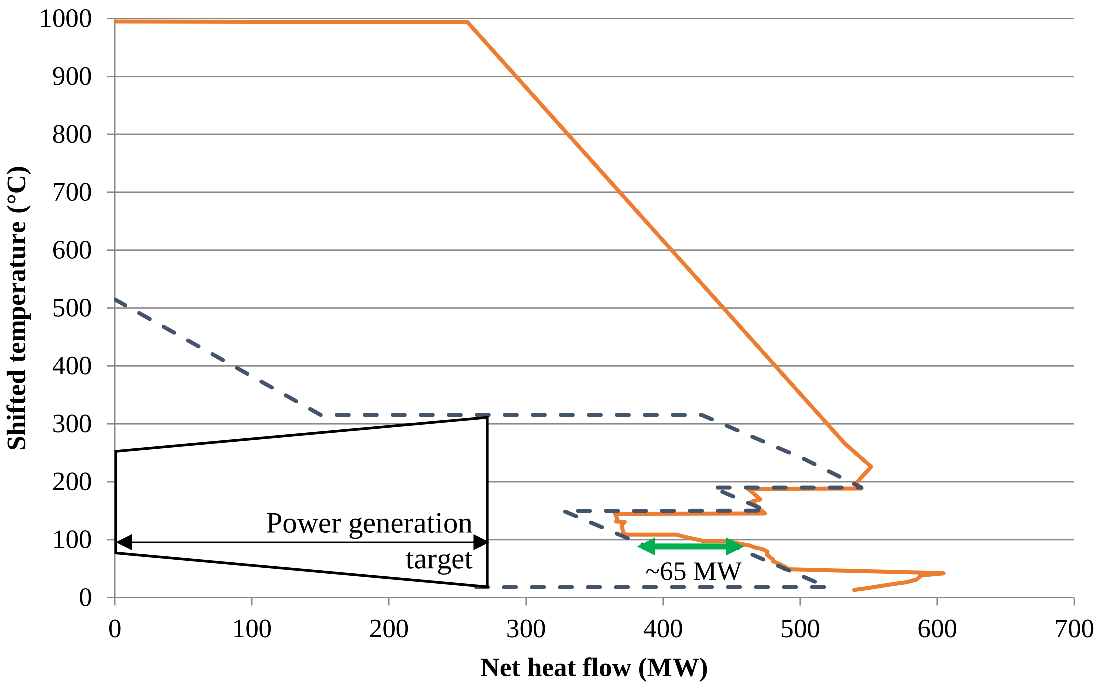

Figure 4. Grand composite curve of the pulp mill including heat from the recovery boiler (orange, solid line) and integrated steam cycle including a condensing stage (blue, dashed line). Potential availability of useful excess heat indicated by green arrow. ΔT_{min} is set individually for each process stream according to stream data as presented in Appendix B.

It should be noted that only current deliveries of district heating (approximately 32 MW) are included in the heating demands of the pulp mill. If the district heating deliveries are increased after the mill reconstruction, the district heating deliveries will be affected if excess heat is used for other purposes.

In addition to this heat, the whole existing bark boiler is available for heat generation. To efficiently make use of this potential heat source, the preferred solution would be to integrate the steam system with both the bark boiler, the recovery boiler, and the carbon capture plant. Figure 5 shows a steam cycle integrated with both the recovery boiler and bark boiler at maximum load. No condensing power generation is assumed in this case, which makes it possible to extract large quantities of heat in the form of low-pressure steam (approx. 350 MW) and process cooling (approx. 100 MW).

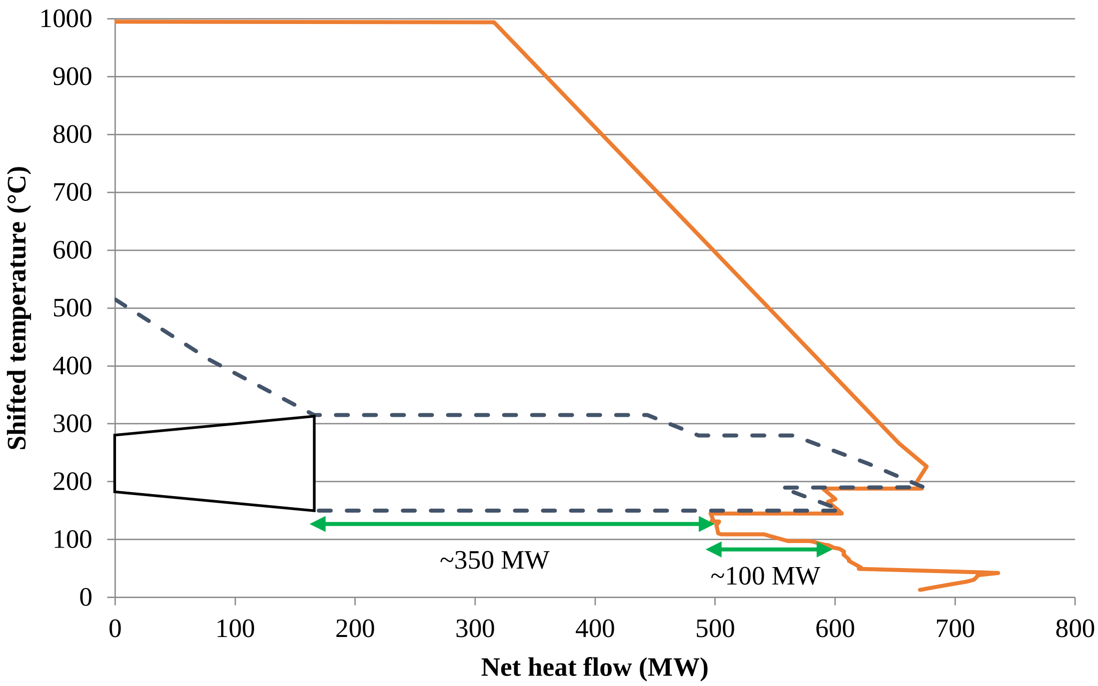

*Figure 5. Integration of steam cycle (blue, dashed line) with the pulp mill process (orange, solid line). The grand composite curve for the pulp mill includes the heat from combustion in the recovery boiler **and** the bark boiler operated at full load. The steam cycle does **not** include a condensing stage. Green arrows indicate potential excess heat availability. ΔT_{min} is set individually for each process stream according to stream data as presented in Appendix B.*

4.3.2 Excess heat availability for the assumed actual process design

The figures above represent a situation with ideal heat integration internally within the pulp mill process. In reality, more than theoretical minimum heating will be needed, and as a consequence the excess heat from the process will also be increased, but it is also likely that the temperature level will be lowered. Consequently, it is likely that the useful excess heat availability is lower for the actual design.

Because we lack access to the final design of the reconstructed process and heat recovery system in the SCA Östrand mill, it is impossible to say what the actual excess heat levels will be. Here, we assume that the mill is built according to the “Realistic retrofit” design proposed by (Ahlström och Benzon, 2015). This design, like the stream data used above, is also available in the case file for the mill. However, to really understand the assumptions behind the design, it was necessary to consult the original report, which was easy to find through references and direct links in the case file. In the report, some changes were also suggested for this design to increase the availability of excess heat at temperatures above 95°C. However, if these changes are actually implemented in the new mill it is likely that this excess heat is used for increased district heating deliveries. Nevertheless, independently of whether the heat recovery system is designed for maximized excess heat or not, it can be assumed that either the proposed levels of excess heat *are* available or *can be made* available by some retrofits in the heat recovery system of the mill.

In Figure 6, the red curve shows the heat content of hot process streams in the mill that are either cooled by the hot and warm water system, or not cooled at all (e.g. flue gases). The blue curve shows the heat demand required by the process from the hot and warm water system. By covering the heat demand by low-temperature process streams as illustrated in the figure, heat at higher temperature can be extracted as excess heat for other uses.

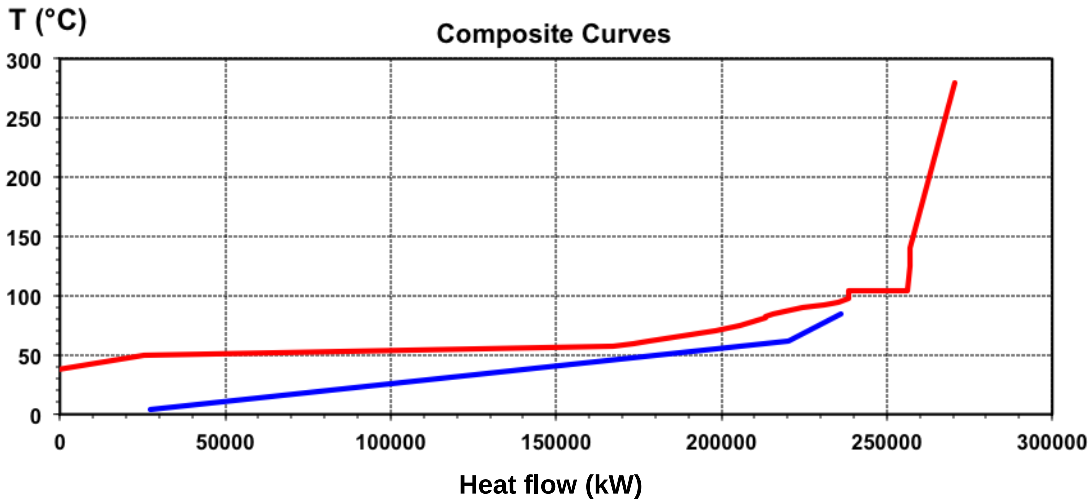

Figure 6. Composite curves showing the heat flow of hot process streams that require cooling or can be used as a potential heat source (red curve), and the heating demand of water flows in the hot and warm water system (blue curve). Blue curve shifted to the left to enable extraction of excess heat from hot streams at the maximum temperature possible. Source: (Ahlström och Benzon 2015).

Note, that this excess heat might also be used for extended district heating deliveries. Ahlström and Benzon (2015) showed how the hot and warm water system could be designed in order to make 65.5 MW of excess heat available for other uses. The process streams supplying this excess heat would all be at temperature above 95°C, which means they could, alternatively, be used to cover a capture process' reboiler duty at around 75°C. About 15 MW of the heat is available at temperatures above 110°C, and could thus be used for a reboiler at 90°C. This heat comes from the flue gases of the lime kiln. Technically, there might be challenges to extract this heat, but according to the thesis, it should be possible.

In this case there also is an excess of steam from the boilers, which is assumed to be used for condensing power generation. In total, it is estimated that about 235 MW of back-pressure steam can be extracted as an excess with this system design if the condensing turbine is taken out of operation, while the bark boiler is still operated at maximum load, see Figure 7.

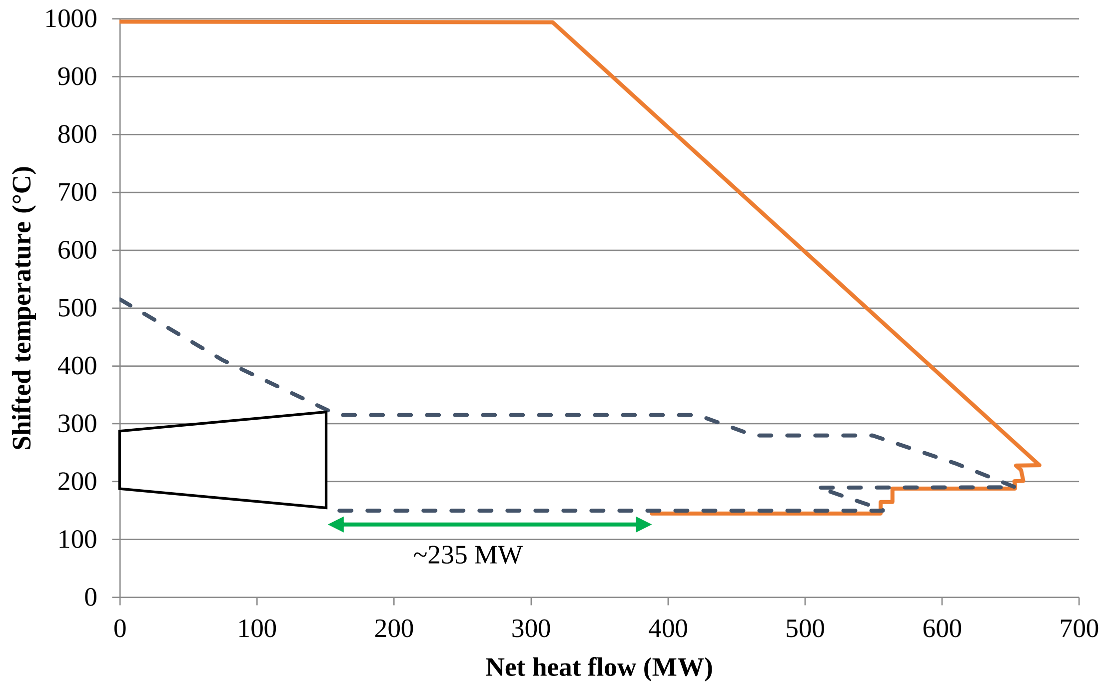

Figure 7. Integration of steam cycle (blue, dashed line) with the pulp mill process current steam demand (orange, solid line). The grand composite curve for the pulp mill includes the heat from combustion in the recovery boiler ***and*** *the bark boiler operated at full load. The steam cycle does* ***not*** *include a condensing stage. Green arrow indicates potential excess heat availability.*

The availability of heat might be somewhat over-estimated due to uncertainties, primarily related to the bark boiler maximum capacity and the recovery boiler load during normal operation. On the other hand, the demand for heating of water depicted by the blue curve in the figure above, includes the heating demand for the condensing turbine condensate. If this is removed, the excess heat availability would increase. Because of difficulties extracting information about how the condensate heating has been modelled in the pinch data, this correction has not been made here. However, while a reduced heat demand for water heating would increase the excess heat availability, the increase would be mainly in the form of heat at below 95°C.

Finally, even more steam could be made available for the capture process if the back-pressure turbine would be by-passed, thus increasing the flow of low-pressure steam while reducing the electricity generation.

4.4 Summarizing conclusions from the example

For a likely design of the heat recovery system in the mill, it is estimated that it would be possible to extract almost 235 MW of low-pressure (4.7 bar) steam and an additional 65.5 MW of heat at lower temperatures, but still above 95°C. The low-temperature excess heat is suitable for a capture process operating with a reboiler temperature of around 75°C, but not higher.

While the numbers for the steam excess might be somewhat overestimated, they are still far lower than the potentials estimated for the ideally integrated process, in which it would be possible to get 350 MW of steam excess and additionally 100 MW of high temperature process excess heat.

This analysis of excess heat availability, including the integration of the steam power cycles had not been performed in the previous study, and the case file included no relevant data about excess heat availability that was directly useful for the assessment of excess heat for carbon capture. However, the analysis presented here was made possible by using data readily available in the case file for the SCA Östrand mill, which was complemented only by some information about boiler capacities from an environmental permit application.

4.5 Comparison with another type of pulp mill

After the reconstruction, the SCA Östrand mill will be one of the largest, and most modern pulp mills in Sweden. Furthermore, the excess heat availability from a market Kraft pulp mill such as the Östrand mill will be higher than that from an integrated mill in which heat is also required for paper production. The analysed mill can therefore not be considered to be representative for a typical, average type of pulp mill in Sweden.

As a comparison, some results for the Holmen Iggesund integrated pulp and paperboard mill are also presented and discussed here, see Swing Gustafsson (2013). In the Iggesund mill, the bark boiler is needed during normal operation, generating around 78 MW of steam at 61 bar. High-pressure steam from the recovery boiler and bark boiler is used for electricity generation in a back-pressure turbine. It has not been possible to find data about the capacity of the bio boiler, but it is reasonable to assume that the boiler is operated close to maximum capacity during normal operation.

The mill exports around 12 MW of heat in the form of low-pressure steam to the co-located sawmill. This heat could – possibly – be used for the capture process if the sawmill heat demand can be covered by other heat sources. The mill also delivers heat to a nearby district heating network. However, this heat demand was not included in the analysis, thereby implying that this heat needs to be supplied from another source.

Figure 8 shows the so-called ACLC (Actual Cooling Load Curve) for the Holmen Iggesund paperboard mill. The ACLC shows the temperature-heat load profile of process streams that are currently cooled by utility (e.g. cooling water or air) in the mill. It is possible to see that about 10 MW of heat is available at temperatures above 105°C, while the rest of the heat is available at significantly lower temperatures, approximately below 70°C. Consequently, about 10 MW of heat could be released and used for a capture process with a reboiler temperatures of 95°C or lower.

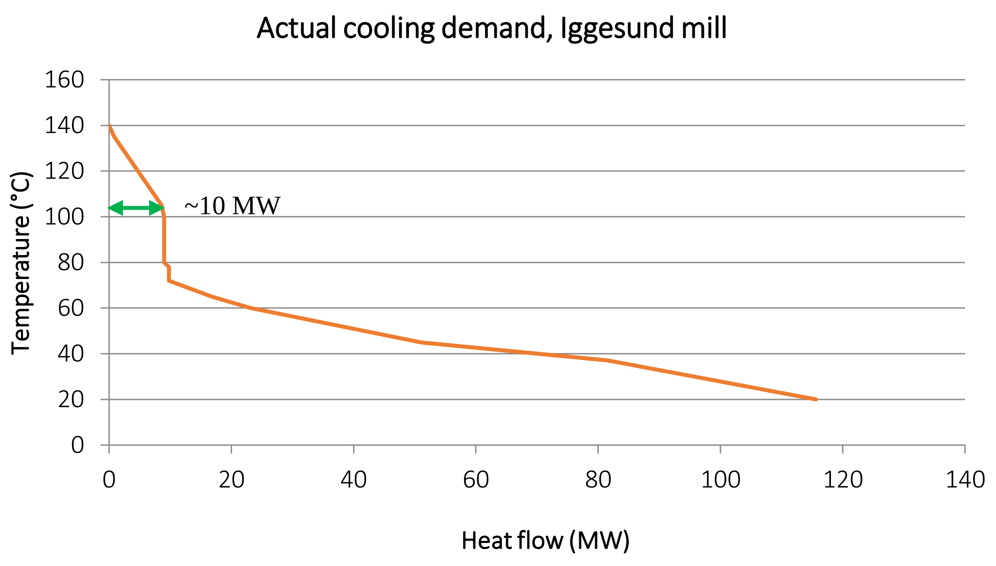

Figure 8. ACLC showing the actual cooling demand of the Iggesund paperboard mill. Green arrow indicates potential availability of useful excess heat. Adapted from Swing Gustafsson (2013).

To summarize, the heat availability from the integrated Iggesund mill is significantly lower than the heat availability from the Östrand mill. Especially the amount of excess heat in the form of steam is much higher in the reconstructed Östrand mill due to the existence of a large bio boiler that is not needed for normal operation of the mill.

In contrast to the analysis of the Östrand mill, where further analyses were needed to be able to estimate the available excess heat for carbon capture, relevant excess heat assessments were already available for the Iggesund mill (e.g. the ACLC curve shown in Figure 8 was directly available in the case file).

5 Using the portfolio for assessing sector-wide potentials for Swedish industry – Example of excess heat availability for carbon capture

This section describes how *Chalmers Industrial Case Study Portfolio* was used to estimate the potential for excess heat driven post combustion carbon capture and storage (EHPC-CCS) in Swedish industry. Like the example presented in Section 4, this task was part of a research project aiming at decreasing the costs for carbon capture through the use of a novel solvent, which amongst other properties would allow for lower regeneration temperatures.

5.1 Assumptions, scope and delimitations

To calculate the required estimate, an inventory of Swedish industrial sites and their excess heat levels in relation to their CO_2 emissions was required. Because of the economics of scale involved in CCS projects, the inventory was limited to include sites with CO_2 emissions above 500 000 tonnes/year. While the specific energy requirement for CO_2 capture (MJ/kgCO_2) depends on several factors, such as flue gas CO_2 content and solvent used, it was decided to use a rough heating demand of 3 MJ/kg of CO_2 captured as a base case for the screening of sites. Using this simplification, the energy requirement for capture of all CO_2 emitted at a certain site can be estimated directly from the on-site CO_2 emissions. A comparison with the available excess heat provides an indication of the feasibility of EHPC-CCS at the site, and it was decided that excess heat must be sufficient for capture of at least one third of the emitted CO_2 for EHPC-CCS to be feasible. Below, this condition is referred to as the “one-third limit”.

In this context, *available* excess heat may include currently utilised excess heat, e.g. for condensing power generation, or may refer to heat than can be made available through investment in new equipment or systems solutions, e.g. waste heat boilers or retrofits of heat exchanger networks. This means EHPC-CCS can be in conflict with current and/or future alternative ways of utilizing the excess heat. For sites *with* sufficient information for a site-specific assessment of excess heat availability, it is assumed that current district heating deliveries are left untouched, i.e. the estimated availability of excess heat for these sites should not compete with district heating.

As described in the introduction of Section 0, the temperature requirements for the excess heat were set at either 95 °C or 110 °C, while also roughly estimating the conditions for amine capture which would require excess heat temperatures above 140 °C.

With the methodology outlined above, the task of estimating the potential for EHPC-CCS in Swedish industry is limited to identifying sites where CO_2 emissions exceed 500 000 tonnes/year and the available excess heat, at temperatures above either 95 °C or 110 °C, is estimated to cover at least the energy requirement for capture of one third of the emissions (that is, > 1 MJ/kg CO_2 emitted).

5.2 Using ChICaSP to estimate the potential for excess heat-driven carbon capture in Swedish industry

All Swedish industrial sites emitting more than 50 000 tonnes CO_2/year are included in ChICaSP and their CO_2 emissions are available. This makes identification of the relevant industrial sites an easy task. In total, there are 27 industrial sites (not counting LUKAB, which is considered an integrated part of the SSAB Luleå site) emitting more than 500 000 tonnes/year. However, estimates on excess heat are *not* generally available and the quality of the estimates is irregular. Table 6 lists the 27 sites and indicates whether case files are available, whether these include data on excess heat, and whether they are based on case studies from Chalmers. Note that all this information is directly available in the summary file of ChICaSP. Distinguishing files based on Chalmers-data from other files is important since for Chalmers-files, project data archives are available, which sometimes enables further analysis.

Of the 27 industrial sites included in the analysis, 14 have a case file in ChICaSP. Of those 14 files, 10 contain information which is sufficient to classify the corresponding sites as above or below the one-third limit, either quantitatively or qualitatively. Three of the exceptions are pulp mills for which the case file data is judged to be outdated. The last one is based on a non-Chalmers study, for which no excess heat assessment was made. For six of the sites a *quantitative* estimate (MJ/kgCO_2) of excess heat at temperatures suitable for CCS can be established, either directly from data for excess heat available in the case files, or via calculations based on other data available via the portfolio (like the example described in Section 0). Out of the 13 sites without case files, one can be classified directly using site-specific information in the case study portfolio. For this site, reports and MSc theses are cited in the portfolio, and these documents provide indications about the site's availability of excess heat. All in all, 11 out of 27 sites (41 %) can be classified using site-specific information directly available in ChICaSP.

Of the remaining 16 sites, for which a classification was not possible using information from ChICaSP, 14 are pulp and paper mills. Models of average, typical Scandinavian mills has been developed for various types of pulp- and paper mills (Kraft market pulp mills, TMP mills, integrated and non-integrated mills etc.), mainly within the Swedish research program FRAM (Future Resource Adapted Mill), see e.g. Delin, et al. (2005) and similar initiatives. Data from these models has been used in various heat integration studies, based on which excess heat potentials can also be estimated and a general knowledge about typical excess heat levels in pulp and paper mills has been developed. Information about the type of mill at each site is available in ChICaSP and can be combined with the model mill results to give an indication on the likely quantity and quality of available excess heat. Consequently, excess heat at integrated mills is assumed to be available at too low temperatures to be useful for carbon capture. The remaining four non-integrated Kraft pulp mills have also been classified below the one-third limit, even though this type of mill generally can generate an excess of steam from their black liquor. However, for some of these mills, there are publications (cited in ChICaSP) reporting results from site-specific energy studies, and nothing there indicates that significant amounts of steam can be made available.

After classifying the pulp and paper mills, two sites which cannot be classified using site-specific data in ChICaSP remain. These are a cement plant and an oil refinery. Beyond the information in ChICaSP, no other data source is readily available for these sites and rough estimates were made by extrapolating from similar sites in ChICaSP. Consequently, these estimates are especially uncertain.

Table 6 summarizes the results of the inventory and indicates if sites are estimated to be above or below the one-third limit, as well as how the estimate was made. For most sites classified as above the limit, the classification holds regardless of which solvent is used in the capture process (i.e., regardless of whether the required excess heat temperature is 95, 110 or 140 °C). However, there are a few sites, as indicated in Table 6, for which the one-third limit is reached only if the temperature requirement for capture can be decreased to 110 or 95 °C.

Table 6: The 27 industrial sites investigated during the excess heat inventory, with indications of the type of information available for each site, their estimated indicative excess heat availability and the method used for estimation.

ID	Site	Case file available	Case study from Chalmers	Previous EH assessment available[a]	Sufficient excess heat[b]	Type of estimate[c]
Mi-1	Cementa Slitefabriken				Yes	Other
PP-1	Södra Cell Mönsterås	√	√		Yes	Quant.
PP-2	Stora Enso Skutskär	√			No	Other
PP-3	Metsä Board Husum				No	Other
IS-1/2[d]	SSAB Luleå & Lulekraft	√	√	√	Yes	Quant.
IS-3	SSAB Oxelösund				Yes	Qual.
R-1	Preemraff Lysekil	√	√	√	Yes[e]	Quant.
PP-4	BillerudKorsnäs Gruvön				No	Other
PP-5	BillerudKorsnäs Gävle				No	Other
PP-6[g]	SCA Östrand	√	√		Yes	Quant.
PP-7	Smurfit Kappa Kraftliner Piteå				No	Other
PP-8	BillerudKorsnäs Skärblacka				No	Other
PP-9	Södra Cell Mörrum	√	√	√	No	Other
PP-10[g]	Södra Cell Värö	√	√	√	Yes	Qual.
PP-11	Stora Enso Skoghall	√	√		No	Other
PP-12	Holmen Iggesund	√	√	√	No	Quant.
PP-13	BillerudKorsnäs Karlsborg	√	√		No	Qual.
PP-14	Stora Enso Nymölla	√			No	Other
PP-15	SCA Munksund				No	Other
PP-16	BillerudKorsnäs Frövi				No	Other
C-1	Borealis Krackeranläggning	√	√	√	Yes[f]	Other
PP-17	Mondi Dynäs	√			No	Qual.
PP-18	Rottneros, Vallviks Bruk				No	Other
PP-19	Nordic Paper Bäckhammar				No	Other
R-2	St1 Refinery				Yes[e]	Other
R-3	Preemraff Göteborg	√	√	√	Yes[e]	Quant.
PP-20	Domsjö Fabriker				No	Other

[a] Useful excess heat assessment from earlier studies available in case file.
[b] Available excess heat estimated to cover the energy requirements for capture of roughly one-third of the site emissions.
[c] Method for excess heat estimation: Quant.) Quantitative estimate based on information in ChICaSP, Qual.) Qualitative assessment based on information in ChICaSP, Other) Estimate based on comparison with models or similar sites.
[d] IS-1 is a CHP plant integrated with the IS-2 steel mill, considered as one integrated site in this assessment.
[e] Excess heat availability strongly dependent on temperature requirement. Estimated availability established for an excess heat temperature requirement of 110°C and is likely to too optimistic in the case of amine capture.
[f] Excess heat assumed to be available also from neighbouring process plants in industrial cluster. Excess heat availability strongly dependent on temperature requirement. Estimated availability established for an excess heat temperature requirement of 95°C and is likely to be too optimistic in the case of higher required temperature levels.
[g] Mill increased capacity significantly after 2016. Excess heat estimation made for prospective future production levels and site energy system.

This example illustrates the importance of the more detailed case files for making inventories and more aggregated assessment of, e.g., sector- or regional potentials. For sites with a case file, 10 out of 14 sites could be classified as above or below the one third limit using the site-specific information in ChICaSP. For sites without case file, the corresponding numbers were 1 out of 14. Consequently, additional case studies would significantly improve the usefulness of the portfolio. However, even for sites where no case file is available, the case study portfolio was a valuable aid when performing the inventory described above. All relevant sites were easily identified and since information on the type of process used at a site is directly available, experience and other sources could be used to make an assessment.

6 Concluding remarks

To enable modelling, assessment and comparison of different technology pathways for the industrial energy transition, there is a need for site-specific data that describes industrial energy use on a level of detail which makes it possible to analyse how energy balances and emissions can be assumed to change over time. *Chalmers Industrial Case Study Portfolio* contains a large number of case studies from Swedish industry, that include information about the energy systems of the industrial plants including the heating and cooling demands of individual industrial processes.

This report describes the structure and content of the portfolio, and also presents two related examples of how data from the case study portfolio can be applied for further assessments. The examples demonstrate how detailed case study data can enable new kinds of analysis, as well as how the aggregated portfolio can be used to draw more general conclusions about the potential for new technology or systems solutions. However, the examples are far from capturing and illustrating the full potential of having access to a collection of a large number of case studies for industrial energy systems analysis. In these times of required rapid change for radical emission reductions, the main opportunity offered by the case study data is assumed to be related to prospective assessments of different decarbonisation pathways, for example: How will industrial excess heat availability change if current heat-driven industrial processes are replaced by electrified processes? How will the energy balances of pulp mills change by the implementation of different types of biorefinery concepts?

Future projects will provide more illustrative examples of how the case study portfolio can be used as a resource for answering this type of questions.

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Appendix A – Selected content from the ChICaSP Summary file

The figure below shows some selected columns of the ChICaSP Summary file for the sites with highest reported total CO_2 emissions in 2016. For a complete list of content covered in the Summary file, please see Section 3, Table 1 The information has been translated from Swedish for the purpose of this report.

Site-ID	Site	County	Municipality	Total CO2 2016 (ton)	Electricity consumption 2016 (or last available environmental report) (GWh, net)	Annual production, or similar, 2016 if not stated otherwise	Case file in Case study portfolio	Main year for reported data	Pinch data	Environmental report or similar available in portfolio	Chalmers study, Ref-ID	Non-Chalmers study, Ref-ID
Mi-1	Cementa Slitefabriken	Gotland	Gotland	1 903 887	Confidential	1,7 Mton cement	-			yes		
PP-1	Södra Cell Mönsterås	Kalmar	Mönsterås	1 833 871	546	721 kton market pulp	yes - Chalmers	2017	yes	no	CTH-NIH2017; CTH-BOK2018	
PP-2	Stora Enso Skutskär	Uppsala	Älvkarleby	1 826 328	410	540 kton market pulp	yes - non-Chalmers	2002	-	yes		LiU-2007
IS-1	Lulekraft LUKAB	Norrbotten	Luleå	1 794 919						no		
PP-3	Metsä Board Husum	Västernorrland	Örnsköldsvik	1 543 453	721	238 kton market pulp + 401 kton paper/board	-			no		
IS-2	SSAB Luleå	Norrbotten	Luleå	1 510 961	355	2,1 Mton prime steel slabs	yes - Chalmers	ca 2007	yes	yes	CTH-GRI2013; CTH-ISA2011; CTH-ISA2010a; CTH-SWI2013	LiU-2011; LTU-2003; LTU-2006
IS-3	SSAB Oxelösund	Södermanland	Oxelösund	1 501 718	446	1,3 Mton prime steel slabs, 0,5 Mton steel plates	-			yes		KTH-2015; KTH-2016
R-1	Preemraff Lysekil	Västra Götaland	Lysekil	1 428 122	524	10,9 Mton crude oil	yes - Chalmers	2010	yes	yes	CTH-AND2013; CTH-AND2016; CTH-AND2014a; CTH-ERI2015a; CTH-SUB2016; CTH-ÅSB2014	
PP-4	BillerudKorsnäs Gruvön	Värmland	Grums	1 295 578	702	111 kton market pulp + 592 kton paper/board	-			no		KAU-2015
PP-5	BillerudKorsnäs Gävle (Korsnärsverken)	Gävleborg	Gävle	1 256 049	887	707 kton paper/board	-			no		
PP-6	SCA Östrand	Västernorrland	Timrå	1 166 416	486	500 kton market pulp	yes - Chalmers	2014/15 up-scaled	yes	yes	CTH-AHL2015	
PP-7	Smurfit Kappa Kraftliner Piteå	Norrbotten	Piteå	1 133 103	587	692 kton paper/board	-			no		LTU-2008; UmU-2013; LTU-2016
PP-8	BillerudKorsnäs Skärblacka	Östergötland	Norrköping	1 007 489		102 kton market pulp + 341 kton paper/board	-			no		
PP-9	Södra Cell Mörrum	Blekinge	Karlshamn	968 872	320	378 kton market pulp	yes - Chalmers	2005/06	yes - partly	no	CTH-PER2009; CTH-PER2010; CTH-LUN2008	
PP-10	Södra Cell Värö	Halland	Varberg	968 473	284	331 kton market pulp	yes - Chalmers	2017	yes	no	CTH-PED2017; CTH-HED2015	
PP-11	Stora Enso Skoghall	Värmland	Hammarö	942 634	907	758 kton market pulp	yes - Chalmers	2001 up-scaled	yes - partly	yes	CTH-EKS2002; CTH-BEN2004; CTH-BEN2002a; CTH-BEN2002b; CTH-MAT2013	
PP-12	Holmen Iggesund	Gävleborg	Hudiksvall	910 739	477	56 kton market pulp + 349 kton paper/board	yes - Chalmers	2010/11	yes	no	CTH-GLA2011; CTH-SWI2013; CTH-ISA2013; CTH-ISA2014	UmU-2015

Appendix B – Selected excerpts from the case file for SCA Östrand

The following tables and figures are directly taken from the case file for SCA Östrand in ChICaSP. To enable a clear presentation of the content in the format of this report, only a selection of the content available in the case file is presented here. Some data sheets have been left out entirely, and for the included tables, some columns and sections have also been omitted.

Main material and energy flows from and to the industrial site		
Main Product(s)	**Reported values * Production** tonnes/year	**Values representing energy study conditions ** Production** tonnes/year
Kraft pulp	411 000	900 000
CTMP	90 000	95 000
Energy input	**Use** GWh/year	**Use** GWh/year
Electricity (purchased)	159,8	
Biobased fuels	2963	
Fossil fuels	101	
CO2 emissions	**Emissions** ktonnes/year	**Emissions** tonnes/year
Fossil	31,7	
Biogenic	1134,7	
Other GHG emissions as CO2_eq		
Electricity generation	**Generation** GWh/year	**Generation** GWh/year
Generated electricity	326,4	depends on new design
Energy or material flow to/from other industry or district heating system	**Flow** GWh/year	**Flow** GWh/year
District heating	173	min 173

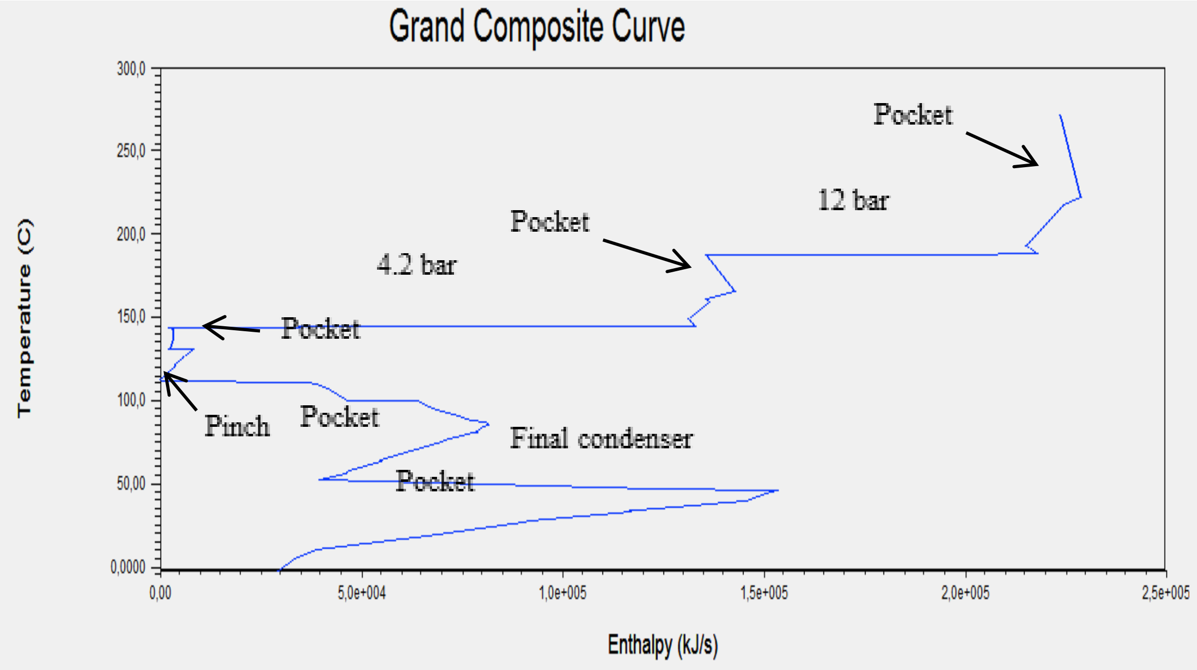
* Publicly reported values for 2016. From Swedish Pollutant Release and Transfer Register (SEPA, 2016b) and "Skogsindustriernas miljödatabas" (Forest industries environmental database) (Skogsindustrierna, 2016)
** Values corresponding to the conditions assumed for the data reported in the case file. In this case, representing a future reconstruction of the mill with doubled capacity.

Background information about the pinch analysis study

Source:	Ahlström and Benzon (2015), data archive (see sheet General information)
Purpose of original pinch study:	identification of heat integration opportunities in a prospective design of a future reconstruction of the mill
Operating scenario for data extraction:	mainly based on quotations for the reconstructed plant, complemented by up-scaled data from a stable winter operating period in the mill
Time period for which data was collected:	30th Oct 2014 - 12th Feb 2015: up-scaled

Composite curves / Grand composite curves

Individual ΔT_{min} according to stream data table.



Stream data

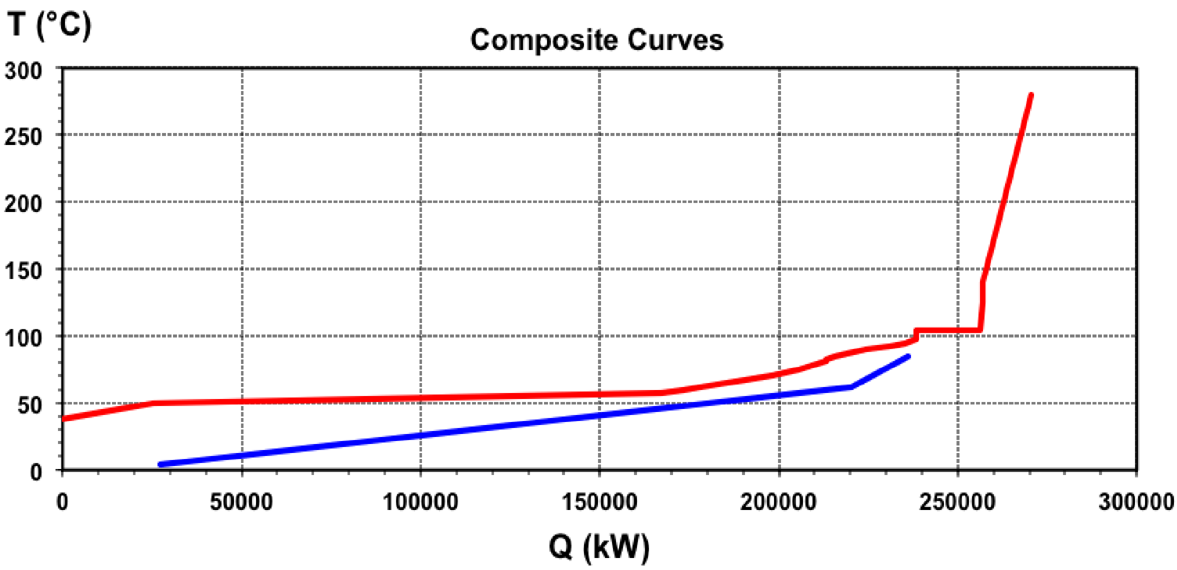
Name	Type *Hot/Cold*	T_{start} *dC*	T_{target} *dC*	Q *MW*	ΔT/2 *K*
Moist air from TM5	Hot	115	37	21.79	10
Moist air from TM6	Hot	115	37	63.93	10
Moist air from CTMP dryer	Hot	49.9	37	14.21	10
Final condenser	Hot	57	50	127.14	8
Gas from "im" condenser	Hot	92	45	13.48	14
Flue gases from bio boiler	Hot	200	150	2.85	14
Flue gases from gas boiler	Hot	275	65	1.92	14
Flue gases from lime kiln	Hot	280	150	12.72	14
Weak liquor to evaporation	Hot	116.6	90	40.14	6
Effluent after OP stage	Hot	81	38	46.83	7
Effluent after Q/D0 stage	Hot	70	38	32.64	7

Liquor to digester	Hot	92	85	8.29	6
Liquor after second oxygen step	Hot	100	94	0.79	6
Effluent in CTMP	Hot	85	60	2.32	7
Cooling of water in CTMP	Hot	85	60	2.32	5
Condensate from process	Hot	129.2	42	44.12	5
Green liquor	Hot	98	82	9.28	7
Flue gases from recovery boiler	Hot	225	140	28.94	14
Turpentine condenser T11A (cooling)	Hot	125.1	104.56	0.51	7
Turpentine condenser T11A (condensation)	Hot	104.56	104.5	17.88	7
Turpentine condenser T20	Hot	104	59.95	0.028	8
Flash steam from weak liquor	Hot	115.43	115.3	35.62	0
Air to TM5	Cold	-2.5	130	4.79	16
Air to TM6	Cold	-2.5	130	14.06	16
Air to CTMP dryer	Cold	-2.5	114.2	6.35	16
LP steam to evaporation	Cold	144.9	145	98.51	0
MP steam to evaporation	Cold	179.9	188	19.66	0
Air to bio boiler	Cold	-2.5	50	2.60	16
Air to gas boiler	Cold	-2.5	50	0.38	16
Air to lime kiln	Cold	-2.5	105	9.88	16
MP steam to digester	Cold	179.9	188	32.55	0
Chip bin	Cold	-2.5	65	35.62	0
Heating of new locals	Cold	25	45	27.94	6
Heating of existing locals and old bleaching plant	Cold	25	45	1.21	6
Wood room	Cold	33	38	19.0	5
MP steam to O2 stage	Cold	179.9	188	6.75	0
MP steam to Q/D1 and PO	Cold	179.9	188	19.72	0
MP steam in CTMP	Cold	188	188	1.81	0
Raff steam in CTMP	Cold	133	133.1	6.36	0
LP steam in resin cooking	Cold	144.9	145	0.39	0
Preheating of white liquor	Cold	91.4	140	7,00	6
Deduction heating of white liquor	Cold	159.5	163.5	8.46	6
Heating of Dynasandwater	Cold	8	17	2.14	5
Water to Mavatank 1 and 2	Cold	17	25	1.91	5
Heating of water to Mavatank 1	Cold	32.3	105	65.08	5
Heating of water to Mavatank 2	Cold	32.3	122	8.37	5
Heating of water from Mavatank 1 into SP6 A	Cold	147.4	157	8.41	5
Heating of water from Mavatank 1 into SP6 B	Cold	192	221	25.41	5
Air preheating into SP6	Cold	-2.5	180	32.82	16
LP steam to Mavatank 1 and 2	Cold	144.9	145	27.18	0
MP steam to ClO2	Cold	179.9	188	2.23	0
LP steam to ClO2	Cold	144.9	145	0.22	0
Preheating of ClO2	Cold	10	45	5.17	5
Process demand cold water	Cold	8	45	59.44	5
Process demand warm water	Cold	45	62	26.97	5
Process demand hot water	Cold	62	85	32.80	5
EON warm water	Cold	44	84	16.26	5
SEAB warm water	Cold	43	73.6	16.00	5

Estimated excess heat potentials		
Short description	**Potential heat amount** *MW*	**Assumptions**
Excess heat from secondary heating system (producing district heating water with supply temperature 85dC)	65,7	realistic retrofit of prospected design
Excess heat from secondary heating system (producing district heating water with supply temperature 85dC)	32,8	ambitious retrofit of prospected design

Figures/Graphs

Suggested realistic retrofit based on predicted mill process data for capacity increase, Excess heat made available at max temperature.



APPENDIX C – Methodology for targeting of power generation and excess heat

Combined targets for power generation and excess heat deliveries from a site depend on the useful heat available at high temperatures (e.g. from combustion) and on the amount of heat required by the process. In this work, the targets were estimated according to the steps described below. The description is adapted from a previous conference paper (Svensson et al., 2018).

Given the large amounts of high temperature excess heat from black liquor combustion in Kraft pulp mills, excess heat availability is characterized considering that the mills are equipped with a steam turbine system.

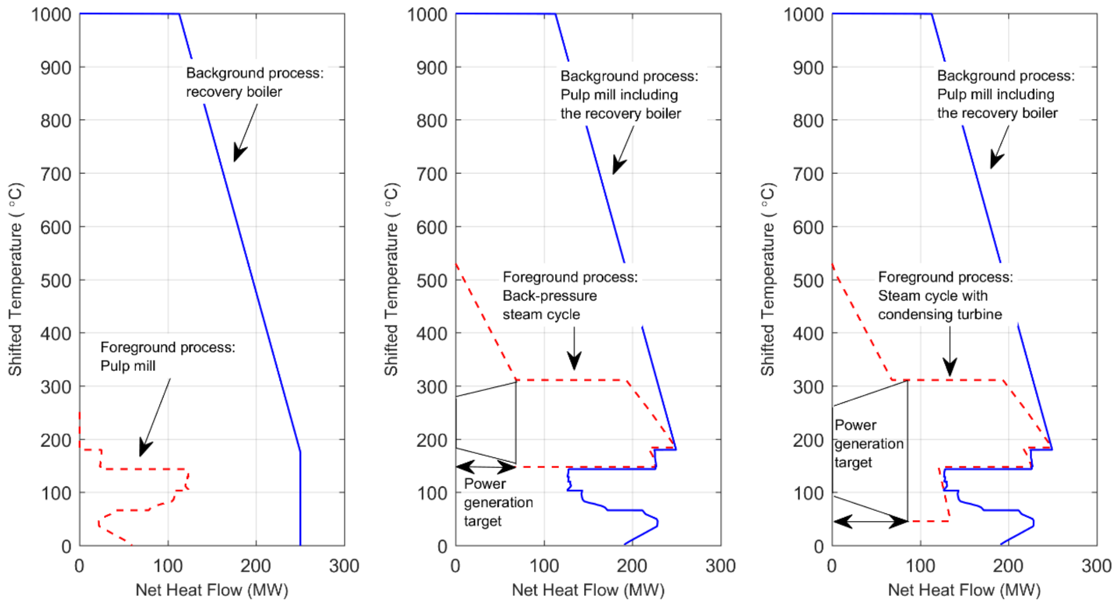


Figure A1. LEFT: Background/foreground analysis using split GCCs of the heat available from black liquor combustion in the recovery boiler and the net heating demand of the process. CENTER: Integration of a back-pressure turbine cycle with the pulp mill process using heat from the recovery boiler. RIGHT: Back-pressure and condensing turbine operation.

1. *Characterization of high-temperature heat from black liquor combustion in the recovery boiler (blue line in Figure A1)*
   Black liquor is combusted in the recovery boiler for recovery of energy and regeneration of cooking chemicals. The boiler size is determined by the amount of black liquor being processed, which in turn depends on the production rate in the pulp digesters. Additional boilers, mainly fuelled with bark, are regarded as part of the utility system and not as necessary parts of the process itself.

2. *Description of process heating and cooling demands for the rest of the pulp mill processes*
   For this step, two different cases can be considered: 1) Net heating and cooling demands after ideal maximized internal process heat recovery, and 2) Current utility requirements for the process for its actual design.

   For case 1), the net process heating and cooling demands for the ideally integrated process are described by the process Grand Composite Curve (GCC) assuming a certain minimum temperature difference for heat exchange (red line in Figure A1). For case 2), the GCC is replaced by a representation of the current heating and cooling demands of the process at different temperatures.

3. *Background/Foreground analysis using split GCCs for black liquor combustion heat and net process heating demand (Figure A1, LEFT)*
   This analysis shows if the heat content from the combustion of black liquor is sufficient to cover the heating demand of the process. When the split GCCs show that there is more heat available from the black liquor than is required by the pulping process, there is a potential for additional power generation without the use of additional fuel. This is the case for the example shown in Figure A1 (LEFT).

4. *Integration of a steam turbine cycle between the black liquor combustion heat from the recovery boiler and the net process heating demand (Figure A1, CENTER)*
   Steam turbine cycle integration is illustrated in a background/foreground graph using split GCCs. In this case, the pulp mill process and the black liquor combustion heat from the recovery boiler are combined into a single background GCC. The steam cycle is represented by another GCC in the foreground.

   Maximum fuel utilization can be achieved with a back-pressure turbine where the low-pressure outlet steam is sufficient to cover the process steam demand. In practice, steam is either available in excess, which opens the opportunity for a condensing turbine stage, or steam is directly reduced to lower pressure, by-passing the turbine. In the latter case, it might be justified to increase the steam production and back-pressure power generation, by firing additional bark in a boiler.

   For the example shown in Figure A1, steam is available in excess. The figure in the centre illustrates pure back-pressure turbine operation and an excess of low-pressure steam that could be delivered as excess heat to an external user. The figure to the right illustrates the case where a condensing turbine is added to the system. This way, the excess of steam is utilized for additional power generation. Note that this system design does not only limit the amount of excess heat available as steam from the steam turbine cycle, but also reduces the amount of excess heat available from the pulp mill process, since this heat is used for heating the condensate from the turbine condenser up to feedwater temperature.

5. *Characterization of excess heat availability for processes with integrated steam cycle*
   The last step is to characterize the availability of excess heat according to its temperature. The resulting temperature profile of excess heat corresponds to the net cooling demand of the total site grand composite curve that includes the process as well as the heat from the boilers and the integrated steam cycle.